Kochi Chapter

Indian Geotechnical Conference
IGC 2022
15th – 17th December, 2022, Kochi

# Assessment of Seismic Stability of Coal Mine Overburden Dump Slope using Random Limit Equilibrium Method (RLEM) and Random Finite Element Method (RFEM) – A Comparative Study

Madhumita Mohanty[1][0000-0002-4271-6432], Rajib Sarkar[2*][0000-0002-7900-3890] and Sarat Kumar Das[3][0000-0002-5627-4233]

[1] Indian Institute of Technology (Indian School of Mines) Dhanbad, Jharkhand, India
madhumita.iitism@gmail.com

[2*] Indian Institute of Technology (Indian School of Mines) Dhanbad, Jharkhand, India
rajib@iitism.ac.in

[3] Indian Institute of Technology (Indian School of Mines) Dhanbad, Jharkhand, India
saratdas@iitism.ac.in

**Abstract.** Adequate knowledge of stability of coal mine overburden (OB) dump in earthquake prone areas is required for proper functioning of the coal mines since unanticipated dump failures may result in the loss of lives and interruption in mining activities. Considering the heterogeneity of the OB dump materials, the spatial variability of the material parameters of coal mine OB dump slope needs to be considered for safe assessment of their stability under seismic forces. Random limit equilibrium method (RLEM) and random finite element method (RFEM), both facilitate in carrying out the probabilistic investigation considering two-dimensional spatial variability. The probabilistic approach in RLEM combines the two-dimensional random field theory with limit equilibrium method, whereas RFEM combines two-dimensional random field theory with finite element method. The current study aims to assess the comparative seismic performance considering a series of isotropic and anisotropic random fields. The pseudostatic analyses of RLEM are performed in the software *Slide2* (Rocscience), whereas the software *OptumG2* is adopted for RFEM analyses. Finally, outcomes obtained from seismic stability analysis of OB dump slope performed with RLEM are compared with the corresponding ones performed using RFEM.

**Keywords:** Coal Mine Overburden Dump Slope, Random Limit Equilibrium Method, Random Finite Element Method, Seismic Slope Stability, Spatial Variability.

## 1 Introduction

The removal and safe disposal of the non-coal waste materials lying above the coal reserves are fundamental operations required to economically exploit the coal existing in the open cast coal mines. Thereafter, these waste materials are transported and dumped at the nearby locations, which results in the formation of coal mine overburden (OB) dumps. The existence of the OB dump in itself is the harbinger of multitude of problems such as exhaustion of precious land area [1], loss of existing species along with the destruction of their habitat [1], endangering the natural environment of the surrounding [2]. The situation aggravates further when OB dump failures occur resulting in burial of houses as well as persons [3]. After a dump failure, the mining activities are disrupted and the regaining of normalcy involves a huge cost [4].

The OB dump slope failures may result due to a single factor or combination of various factors. The shaking of ground due to earthquakes leads to an increase in the likelihood of making the OB dump unstable on account of the inertial force or by the decrease of strength of the dump materials. Thus, pseudostatic approach has been considered in the present study. The OB dump model used in the analyses is comprised of two benches.

While assessing the seismic stability of the OB dump, the spatial variability and uncertainty in the properties of its materials require due consideration. Thus, the random fields developed in the limit equilibrium and finite element software in the present study have been utilized to perform the comparative study. In this paper, the seismic performances evaluated on the basis of random limit equilibrium method (RLEM) and random finite element method (RFEM) have been adequately compared and elucidated. Both the lower and upper bound conditions have been considered in RFEM.

In order to perform RLEM - based investigations, the pseudostatic analyses were done in the software *Slide2* (Rocscience) [5]. Considering similar scenarios, the software *OptumG2* [6] was used for the RFEM analyses. A probabilistic framework was used in performing the analyses in both RLEM as well as RFEM. The angle of friction of the OB dump material was used as the random variable for indicating spatial variability. In both, RLEM and RFEM, the spatial variability was represented along the two dimensions, "*x*" and "*y*" in terms of correlation lengths. With equal correlation lengths along both the axes, an isotropic random field was obtained, whereas with unequal values of correlation lengths, the random field became anisotropic. Thus, the random fields were devised in several isotropic and anisotropic manners in the present work.

The literature based on the implementation of RFEM and RLEM to study the seismic slope stability of coal mine OB is negligible. Therefore, the present study involves a comparison of the two approaches by quantifying the outcomes in terms of probability of failure and the reliability index. For the isotropic random fields, the probability of failure is least for RFEM (upper bound) and greatest for RLEM, vice versa being observed for the reliability index. In case of anisotropic random fields, similar trends were observed.

## 2 Geometrical characteristics of the OB dump model

The geometrical characteristics of the OB dump model have been considered according to the Coal Mines Regulation 2017 [7]. It essentially comprises a base portion, a top bench and a bottom bench. The details of the geometry of the OB dump utilized in the present study have been given in Fig. 1.

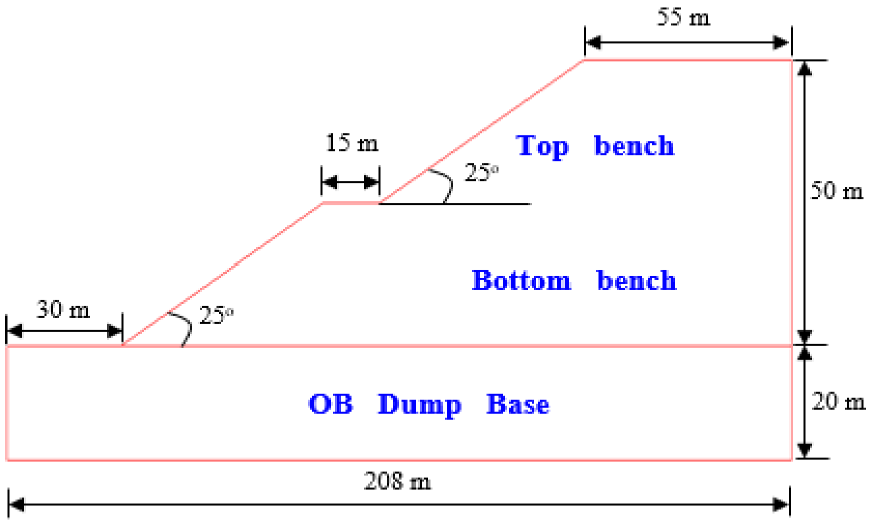


**Fig. 1.** Geometrical characteristics of the OB dump model used in the present study.

## 3 Material properties of the OB dump model

The OB dump situated in Jambad open cast coal mine of India was considered as the area of study. For both the benches, the properties of the OB dump material were decided according to the multi-channel analysis of surface waves (MASW) test and using different correlations [8-10]. Utilizing the log-normal distribution, the mean values of the necessary material properties were determined from the datasets acquired by performing MASW tests on the OB dump slope. The Mohr-Coulomb material model was applied throughout the current study. Generally, sandstone is the widely found material in the Indian coal mine OB dumps, thus, datasets of the properties of several types of sandstones enlisted in Zhang and Sui (2019) [11], were collected. The mean values of the properties (obtained using log-normal distribution) were implemented for the base of the OB dump model, which have been summarized in Table 1.

It is assumed that the effect of spatial variability of the parameters of the OB dump base on its seismic slope stability is negligible since the base is generally of higher strength and significantly lesser spatially variable than the loose OB materials of the slope. This is observed from the field studies at various eastern Indian coal mines. Thus, throughout the investigation, the base was considered as a homogeneous block and the properties mentioned in Table 1 were used as such while modelling the OB dump base.

For both the top and bottom benches of the OB dump, the properties of the material have been considered according to Table 2. It can be seen from Table 2 that cohesion of the material of the benches of the OB dump is practically nil (considering the bench material as cohesionless). Thus, in the present study, the spatial variability of the OB dump materials is considered by using friction angle of the benches of the slope as the random variable with coefficient of variation as 7.473 %.

**Table 1.** Material properties for the base of the OB dump model [adopted from 11].

| Material Property | Unit weight | Elastic Modulus | Poisson's ratio | Cohesion | Friction angle |
|---|---|---|---|---|---|
| Unit | (kN/m$^3$) | (MPa) | _ | (kPa) | (°) |
| Value | 26.05 | 7745 | 0.24 | 8060 | 35.51 |

**Table 2.** Material properties for the benches of the OB dump model.

| Material Property | Unit weight | Elastic Modulus | Poisson's ratio | Cohesion | Friction angle |
|---|---|---|---|---|---|
| Unit | (kN/m$^3$) | (MPa) | _ | (kPa) | (°) |
| Value | 14.50 | 304.85 | 0.35 | 0 | 33.32 |

## 4 Methodology used for RLEM analyses

When the correlation lengths along "*x"* (denoted as "$\Theta_x$") and "*y"* (denoted as "$\Theta_y$") axes are equal, the resulting random field is isotropic and is indicated as $\Theta_{xy}$, whereas if they are unequal, it becomes anisotropic. With the help of RLEM, the probabilistic seismic slope stability analyses were performed for the isotropic random field with "$\Theta_{xy}$" as (i) 1, (ii) 2, (iii) 3 and (iv) 4. The anisotropic random fields (indicated as $\Theta_x$ x $\Theta_y$) used in the study were: (i) 3 x 4 and (ii) 4 x 3.

After generating the OB dump slope model in the software, *Slide2* (Rocscience), the boundary conditions of the slope were automatically devised. Pseudo-static analyses were performed considering the occurrence of "severe" earthquakes; thus, the horizontal seismic coefficient used was 0.1 [12]. For each of the isotropic and anisotropic random fields stated above two hundred Monte-Carlo simulations were performed to evaluate the probability of failure, $P_f$ and reliability index, $\beta$.

## 5 Methodology used for RFEM analyses

To perform the probabilistic seismic slope stability analysis in RFEM, the software *OptumG2* was utilized. Triangular elements were used for meshing the OB dump model. Movement in the *x* and *y* directions were restricted at the bottom of the OB dump model. Along the sides, the movement was restricted in the *x* direction. All the other conditions were kept the same as the RLEM analyses. Thereafter, the finite element limit analysis was used to determine the probability of failure, $P_f$ and reliability index, $\beta$ for the lower bound and upper bound conditions.

## 6 Results and discussions

The comparative study was done considering the outcomes obtained from RLEM, lower bound RFEM and upper bound RFEM analyses. Various isotropic and anisotropic random fields have been considered while carrying out the analyses and the results obtained have been discussed in the forthcoming sections.

### 6.1 Comparative study considering isotropic random field

Four cases of isotropic random fields were considered having "$\Theta_{xy}$" as (i) 1, (ii) 2, (iii) 3 and (iv) 4. The spatial variability for the 3$^{rd}$ case has been represented diagrammatically in Fig. 2 for lower bound RFEM, upper bound RFEM and RLEM.

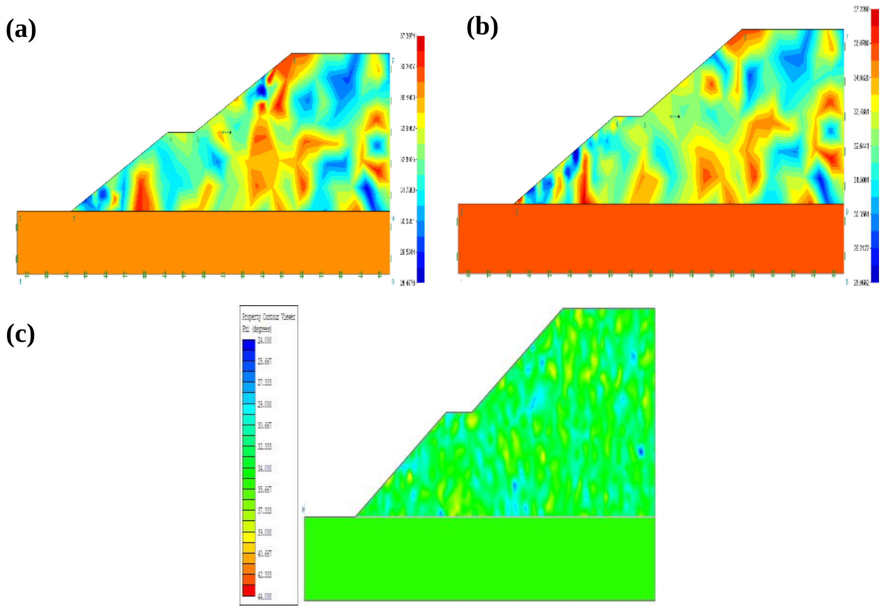


**Fig. 2.** Diagrammatic illustration of spatial variability of the friction angle considering the isotropic random field for "$\Theta_{xy}$ = 3" for: (a) Lower bound RFEM, (b) Upper bound RFEM, and (c) RLEM.

It is observed from Table 3 that for RLEM, the probability of failure stays almost constant irrespective of increase in $\Theta_{xy}$. For RFEM (lower bound), the probability of failure shows a rising trend from 48.5 % to 96 %. Similarly, in case of RFEM (upper bound) the probability of failure rises from 2 % to 63 %. Moreover, it is also noted from Table 3 that the reliability index for RLEM slightly reduces from -1.875 to -2.126. For RFEM (lower bound), the reliability index decreases from -0.11 to -1.53. A similar falling trend is seen in case of RFEM (upper bound), where the reliability index falls from 1.94 to -0.41.

**Table 3.** Details of the comparative study performed for the isotropic random fields.

| Random Field | Isotropic | | | |
|---|---|---|---|---|
| Correlation length of isotropic random field, $\Theta_{xy}$ (m) | 1 | 2 | 3 | 4 |
| RLEM | | | | |
| Probability of failure, $P_f$ (%) | 99.5 | 99.5 | 99.5 | 100 |
| Reliability index, $\beta$ | -1.875 | -1.984 | -2.089 | -2.126 |
| RFEM (Lower bound) | | | | |
| Probability of failure, $P_f$ (%) | 48.5 | 90.0 | 95.5 | 96.0 |
| Reliability index, $\beta$ | -0.11 | -1.23 | -1.56 | -1.53 |
| RFEM (Upper bound) | | | | |
| Probability of failure, $P_f$ (%) | 2.0 | 41.5 | 60.0 | 63.0 |
| Reliability index, $\beta$ | 1.94 | 0.25 | -0.17 | -0.41 |

It is seen from Fig. 3, that for each of the isotropic correlation length, the probability of failure reduces as follows: RLEM > RFEM (lower bound) > RFEM (upper bound). Furthermore, the probability of failure of RLEM tends to remain constant, while that in the cases of lower and upper bound RFEM shows a rising trend.

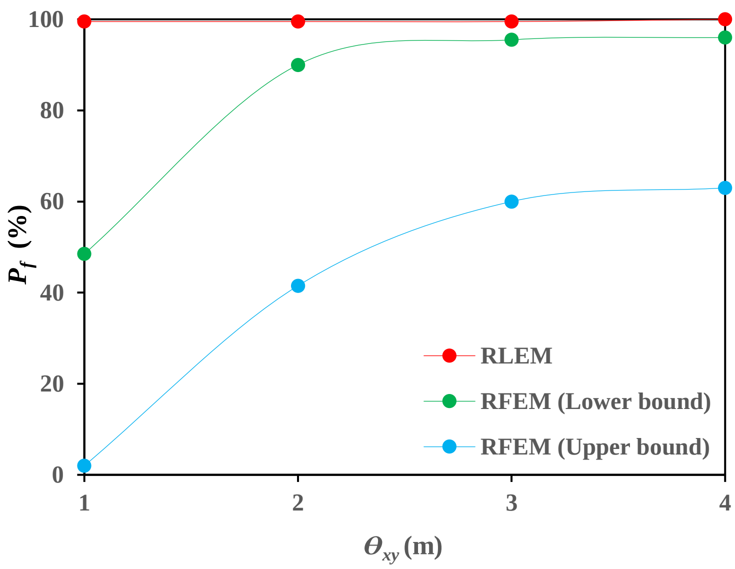


**Fig. 3.** Variation of the probability of failure with correlation length of isotropic random field.

Figure 4 indicates that while considering the isotropic correlation lengths, the reliability index has the following increasing trend for a particular correlation length: RLEM < RFEM (lower bound) < RFEM (upper bound). Furthermore, the reliability index of RLEM tends to show a very slight decrease, whereas a falling trend is observed in the analyses of lower and upper bound RFEM.

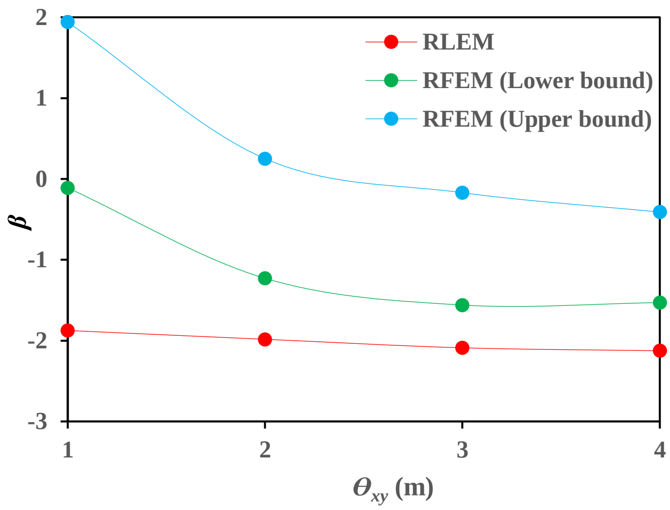


**Fig. 4.** Variation of reliability index with correlation length of isotropic random field.

### 6.2 Comparative study considering anisotropic random field

The anisotropic random fields ($\Theta_x$ x $\Theta_y$) used in the comparative study were: (i) 3 x 4 and (ii) 4 x 3. The pictorial representation for "$\Theta_x$ x $\Theta_y$" of "4 x 3" has been provided in Fig. 5 for lower bound RFEM, upper bound RFEM and RLEM.

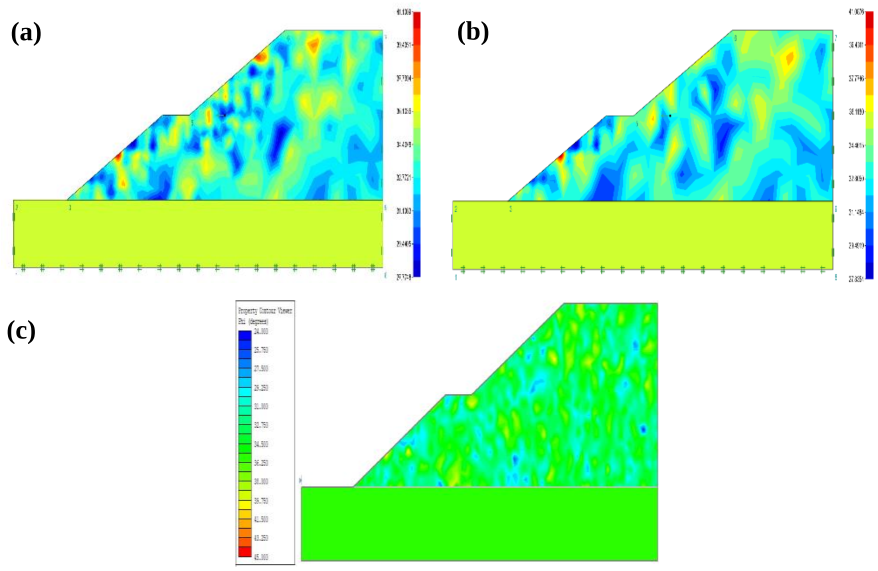


**Fig. 5.** Diagrammatic illustration of spatial variability of the friction angle considering the anisotropic random field, "4 x 3" for: (a) Lower bound RFEM, (b) Upper bound RFEM, and (c) RLEM.

The outcomes of two cases of anisotropic random fields have been considered in the present work. In the 1st case, "$\Theta_x$ x $\Theta_y$" is "3 x 4", while in the 2nd case, "$\Theta_x$ x $\Theta_y$" is "4 x 3". Table 4 shows that for RLEM, the probability of failure is more (100 %) in the 2nd case with that in the 1st case having a slightly lower value (99.5 %). The reverse is seen in case of RFEM, where the values of probability of failure are greater for the 1st case (94 % and 55.5 %) and lesser for the 2nd case (91 % and 54.5 %).

It is further seen from Table 4 that the reliability index is always higher in the 2nd case irrespective of the method of analyses followed. It is seen from Table 4, that for an individual anisotropic correlation length, the probability of failure falls in the following way: RLEM > RFEM (lower bound) > RFEM (upper bound). Moreover, the values of reliability index for a particular anisotropic random field increase in the following manner: RLEM < RFEM (lower bound) < RFEM (upper bound).

**Table 4.** Details of the comparative study performed for the anisotropic random fields.

| Random Field | Anisotropic | |
|---|---|---|
| Correlation length of isotropic random field, $\Theta_x$ (m) x $\Theta_y$ (m) | 3 x 4 | 4 x 3 |
| RLEM | | |
| Probability of failure, $P_f$ (%) | 99.5 | 100 |
| Reliability index, $\beta$ | -2.122 | -2.109 |
| RFEM (Lower bound) | | |
| Probability of failure, $P_f$ (%) | 94.0 | 91.0 |
| Reliability index, $\beta$ | -1.51 | -1.37 |
| RFEM (Upper bound) | | |
| Probability of failure, $P_f$ (%) | 55.5 | 54.5 |
| Reliability index, $\beta$ | -0.23 | -0.19 |

Irrespective of the type of random field considered, it was seen that with the use of RLEM the results are overestimated for probability of failure and underestimated for reliability index. The reason may be attributed to the pre-assumed failure surfaces. Thus, adopting RFEM would be beneficial in representing the spatial variability of the OB dump material in a realistic manner.

## 7 Conclusions

A comparative study was conducted to assess the seismic slope stability based on RLEM and RFEM. In RFEM, both the lower and upper bound values were considered. Pseudostatic analyses were carried out. Probabilistic investigation was done using Monte-Carlo simulations. In each of the isotropic correlation length, the decreasing trend for probability of failure is: RLEM > RFEM (lower bound) > RFEM (upper bound). Again, considering the isotropic correlation lengths, the reliability index has the following increasing trend for a particular correlation length: RLEM < RFEM (lower bound) < RFEM (upper bound). Similar trends were noticed for the anisotropic random fields for probability of failure and reliability index. RLEM overestimates the probability of failure and underestimates the reliability index. Therefore, it would be advantageous to utilize RFEM for the realistic representation of the spatial variability of the OB dump material.

## References


1. Tripathi, N., Singh, R.S., Chaulya, S.K.: Dump stability and soil fertility of a coal mine spoil in Indian dry tropical environment: A long-term study. Environmental Management 50(4), 695–706 (2012).
2. Adibee, N., Osanloo, M., Rahmanpour, M.: Adverse effects of coal mine waste dumps on the environment and their management. Environmental Earth Sciences 70, 1581–1592 (2013).
3. Duc, D.M., Hieu, N.M., Sassa, K., Hamasaki, E., Khang, D.Q., Miyagi, T.: Analysis of a deep-seated landslide in the Phan Me coal mining dump site, Thai Nguyen Province, Vietnam. In: Proceedings of World Landslide Forum 3, pp. 373–377. Springer, Beijing (2014).
4. Wang, J., Chen, C.: Stability analysis of slope at a disused waste dump by two-wedge model. International Journal of Mining, Reclamation and Environment 31(8), 575–588 (2017).
5. Optum G2, Optum computational engineering. Optum G2 (2021).
6. Slide2 v9.020, 2D limit equilibrium slope stability analysis based software. Rocscience Inc, Toronto, Ontario, Canada (2021).
7. Director General of Mines Safety (DGMS): Coal Mines Regulations, Notification, New Delhi, dated 27.11.2017. Ministry of Labor and Employment, Directorate General of Mines Safety (2017).
8. Anbazhagan, P., Uday, A., Moustafa, S.S.R., Al-Arifi, N.S.N.: Correlation of densities with shear wave velocities and SPT N values. Journal of Geophysics and Engineering 13, 320–341 (2016).
9. Barton, N.: The shear strength of rock and rock joints. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts 13(9), 255-279 (1976).
10. Kumar, R., Bhargava, K., Choudhury, D.: Estimation of engineering properties of soils from field SPT using random number generation. INAE Lett; 1, 77–84 (2016).
11. Zhang, D., Sui, W.: Orthogonal array analysis of overburden failure due to mining of multiple coal seams. Journal of the Southern African Institute of Mining and Metallurgy 119(10), 801-810 (2019).
12. Terzaghi, K.: Mechanisms of landslides. Engineering Geology (Berkley) Volume. Geological Society of America (1950).